

Aeroacoustic noise prediction in high speed trains due to attached and detached flow

SORRIBES-PALMER, F.* , ALONSO, G,[†] AND GHAEMI-NASAB, M. [†]

*Universidad Politécnica de Madrid (UPM)
Pza. de Cardenal Cisneros, 3
28040 Madrid, Spain

E-mail: felix.sorribes@upm.es

[†] Universidad Politécnica de Madrid (UPM)
Pza. de Cardenal Cisneros, 3
28040 Madrid, Spain

Email: gustavo.alonso@upm.es, m.ghaemi@upm.es

Key Words: Detached Flows, Computational Methods, Noise Prediction, High Speed Trains

Abstract. This paper aims to set out the influence of the flow field around high speed trains in open field. To achieve this parametric analysis of the sound pressure inside the train was performed.

Three vibroacoustic models of a characteristic train section are used to predict the noise inside the train in open field by using finite element method FEM, boundary element method (BEM) and statistical energy analysis (SEA) depending on the frequency range of analysis. The turbulent boundary layer excitation is implemented as the only airborne noise source, in order to focus on the study of the attached and detached flow in the surface of the train. The power spectral densities of the pressure fluctuation in the train surface proposed by [(Cockburn and Roberson 1974), (Rennison et al. 2009)] are applied on the exterior surface of the structural subsystems in the vibroacoustic models.

An increase in the sound pressure level up to 10 dB can be appreciated due to the detachment of the flow around the train. These results highlight the importance to determine the detached regions prediction, making critical the airborne noise due to turbulent boundary layer.

1. INTRODUCTION

In modern high speed trains aerodynamic noise at speed above 300 km/h is dominant among other sound sources like wheel-rail noise, engine, gearbox, cooling, etc. Vibroacoustic analyses are usually done in train design process in order to optimize the noise control treatments to assure the comfort of the passengers, before the final configuration is frozen.

The aeroacoustics in high speed trains has been studied from many different approaches. Experimentally, the use of microphone array technique in wind tunnels and also real scale, to locate and quantification of the aeroacoustic sound sources has been commonly used (Lauterbach et al. 2010, Gori et al. 2001). The characterized noise sources obtained measurements are used to validate numerical simulations, for near-field propagation and the integration of these aeroacoustic sources within algorithms for far-field propagation (Paradot et al. 2008).

Lightweight, large area structures like high speed trains are very sensitive to acoustic loads. A combined fine element method and boundary element method analysis is needed to simulate the fluid structure interaction at low frequencies (Wijker 2008). At high frequencies due to the amount of

computing time required in FEM and BEM (Chen et al. 2011) a statistical energy analysis (SEA) is often used to predict the vibroacoustic response of the vehicle (Forssén et al. 2011, Králíček and Dupal 2007). Hybrid FE-SEA method are used in middle frequency range (Sapena and Blanchet 2009).

An alternative to the use of the correlations proposed in the literature for the PSD of the pressure in the surface of the train (Cockburn and Roberson 1974), is to simulate the flow with a CFD. Among the major problems in computational aeroacoustics (CAA) there is the filtering of numerical procedure as RANS, URANS and LES of the high frequency and small space fluctuation; this is a common research topic in sound prediction (Lorenzoni 2008). Artificial dispersion and dissipation of numerical schemes can lead to unacceptable attenuation of the sound waves. Especial care should be taken in the truncation of the computational domain to avoid artificial acoustic sources, which is in compromise with the demanding computational time of the simulation.

Direct numerical simulation (DNS) can describe the generation of the smallest structures in the wall and the near acoustic field that they create. But this method is very unsuitable for commercial use due to the large computational time, memory space and accuracy limiting its application to simple flow configurations.

Another direct method used in CAA with computational cost relatively high is direct Large Eddy Simulation (LES), in which only the big turbulent scales are directly resolved. The justification for the use of this method remains in the efficiency of larger scales to radiated noise.

The 3D unsteady flow around a bogie section of a high speed train is solved by LES and the instantaneous flow properties are coupled with the compact Green's function to obtain the distribution of dipole sources in Takaishi et al. 2002. The sound radiated into the streamwise direction is predicted by Howe's equation in agreement with Curl's formula.

The Reynolds Averaged Navier-Stokes equations (RANS) are time averaged equations of motion for fluid flow and are primarily used to describe turbulent flows. The averaging is done in a time small compared with the flow time evolution but large compared to the time-scale of the turbulent fluctuations. The most used models of turbulence are: Reynolds's stress model, $k-\epsilon$ and $k-\omega$. These equations can be used to generate an initial condition for URANS, and obtain the pressure spectral density to use in the vibroacoustic models.

The Detached Eddy Simulation (DES) is the combination of RANS to model the attached boundary layer and LES for the separated region flow field. An external to VAOne simulation to obtain a more precise pressure distribution in the wall of the train could have been introduced in VAOne as a fluctuating pressure surface in low and middle frequency vibroacoustic models or to fit a TBL parameters. A TBL can also be introduced after doing an average over the surface of the SEA structural subsystem.

This paper is focused in the influence of the flow detachment in the airborne excitation for the vibroacoustic model of a high speed train and the effect in the sound pressure level inside and outside the train. In this article the expressions for the PSD of the pressure in the surface proposed by Cockburn and Roberson 1974, is used with different hypothesis of flow detachment and reattachment of the flow.

2. TURBULENT BOUNDARY LAYER EXCITATION IMPLEMENTATION

The airborne noise generated by the turbulent boundary layer is introduced in the program VA One as a pressure power spectral density (PSD), using the expression proposed by (Cockburn and Roberson 1974). The spacial correlation function used in VA One between the pressure fluctuations at any two points on the loaded surface is (Larko and Hughes 2007):

$$R(x, x, \omega) = \left(e^{\left(-c_{\xi}(\omega) \sqrt{k_{\xi}^2(\omega) + k_{\eta}^2(\omega) + \left(\frac{1}{3\delta^*} \right)^2} |\xi| \right)} \cos(k_{\xi}(\omega) \xi) \right) \left(e^{\left(-c_{\eta}(\omega) \sqrt{k_{\xi}^2(\omega) + k_{\eta}^2(\omega) + \left(\frac{1}{3\delta^*} \right)^2} |\eta| \right)} \cos(k_{\eta}(\omega) \eta) \right) \quad (1)$$

where the fractions of the convective wave number along and across the flow are $k_{\xi}(\omega) = \alpha(\omega) \frac{\omega}{U_c}$ and $k_{\eta}(\omega) = \beta(\omega) \frac{\omega}{U_c}$ respectively, and $\delta^* = \frac{\delta}{8} = \frac{0.37}{8} \frac{X_0}{\text{Re}^{1/5}}$ is the TBL thickness, and Re is the Reynolds number and X_0 is the distance to the leading edge of the train. The default parameters for the TBL aligned with the x axis ($\alpha = 1$, $\beta = 0$) have been used. The dimensionless spatial correlation coefficients of decay along and across the flow $c_{\xi}(\omega) = 0.1$, $c_{\eta}(\omega) = 0.72$, a convection velocity $U_c = 0.7U_0$ being U_0 the free stream flow velocity.

The power spectral density of the dynamic pressure in the surface due to the TBL is calculated with the following expression 2.

$$S_p(f) = \frac{P_{RMS}^2}{f_0 \left(1 + \left(\frac{f}{f_0} \right)^A \right)^B} \quad (2)$$

where the root mean square pressure, p_{RMS} , is indicated in the table 1.

Attached	$\frac{p_{RMS}}{q} = \frac{0.006}{1 + 0.14M^2}$
Detached	$\frac{p_{RMS}}{q} = \min \left(0.026, \frac{0.041}{1 + 1.606M^2} \right)$

Table 1: Pressure root mean square for attached and detached flow.

where q, is the dynamic pressure ($q = 1/2 \rho U^2$), M, is the Mach number ($M = U/a$) and f_0 is the reduced frequency, $f_0 = CU_0/\delta$. And the parameters A, B and C depend on the flow configuration and are summarized in the table 2.

	Attached	Separated
A	0.9	0.83
B	2.0	2.15
C	0.346	0.170

Table 2: TBL power spectral density parameter.

3. VIBROACOUSTIC MODELS

In (Sorribes-Palmer et al. 2013) it was already shown that a characteristic section of a train wagon with an equivalent structural and acoustic behaviour is enough to analyse in the first steps of the design of a new train and optimize the noise control treatments (NCT).

The section under study is at 11 meters from tip train's nose and was generated based on typical high speed train structure, with extruded (truss-like cores) and ribbed panels, derived from the examples found in the bibliography.

The model is separated in parts with similar structural properties; a modal analysis of the FEM model was done first to identify the subsystem partitions for SEA modelling. The truss-like cores that compose the structural box were separated in external, core and internal subsystems to facilitate the separation of interior and exterior domains and to make easier the connection to the exterior air.

Open field models for low, middle and high frequencies were developed (see figure 1). External elements as the bogie and the cavity down the train wagon simulate the bogie or the equipment's departments depending on the position of the section in the train. In the created models the condition of rigid walls is applied to this faces or plates (with null acceleration spectra) to decouple the motion of this system from the structural box.

The structure box is pinned and the faces in the air that delimitate the cross section of the train has been supposed as periodic (rigid wall), this approach is highly conservative as the pressure inside is over-predicted. The possible leakage through gaps in gangways on windows has been neglected. The NTC's are connected to the structural box by point junctions. An absorption coefficient for the ballast track of 5% has been assumed.

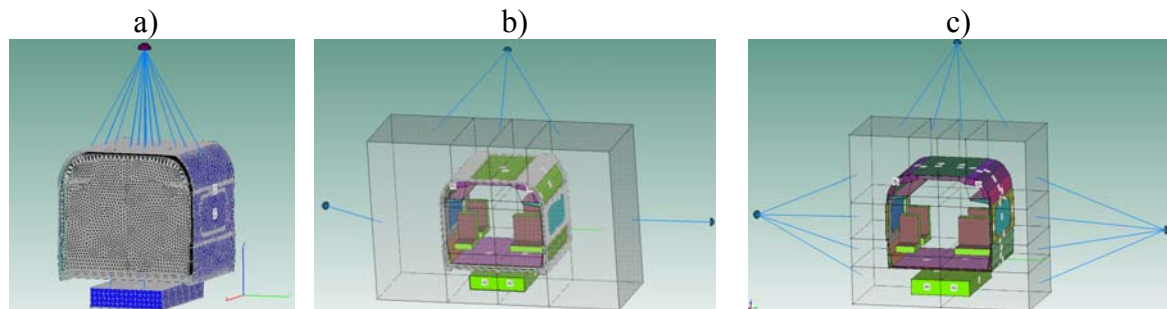


Figure 1: Train section vibroacoustic models for low (a) middle (b) and high (c) frequency range.

In the hybrid model the FE structures are substituted by equivalent SEA plates in which the modal densities, damping loss factors and the coupling loss factors between the plate and the acoustic cavities have been modified. The number of modes per frequency band in 1/3 of octave in the SEA plates was higher than 3 in the frequency bands under study. The known transmission loss of similar subsystems found in the bibliography was applied in the area junctions.

For the validation of the models experimental measurements of the pressure inside the train were recorded with several microphones located at 23 meters from the nose of the train. The SPL of the microphones were used to correlate the vibroacoustic models comparing the SPL averaged in the interior acoustic cavities that simulates the air volume measured with the microphones.

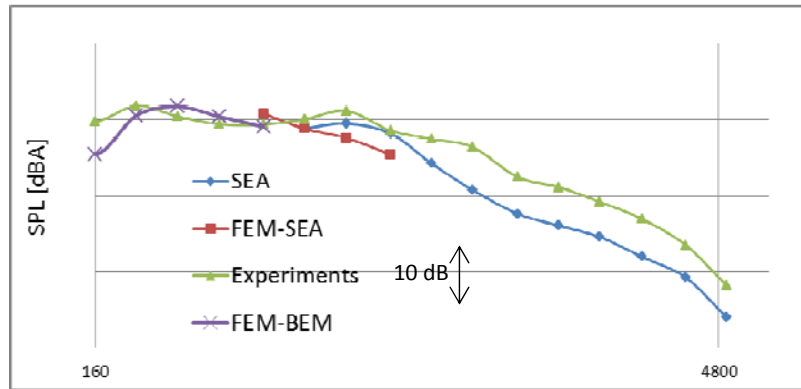


Figure 2: Continuity and validation of vibroacoustic models.

In order to evaluate the influence of the detached flow in the sound pressure level inside the train a model of 2 wagons composed by 23 characteristic train sections.

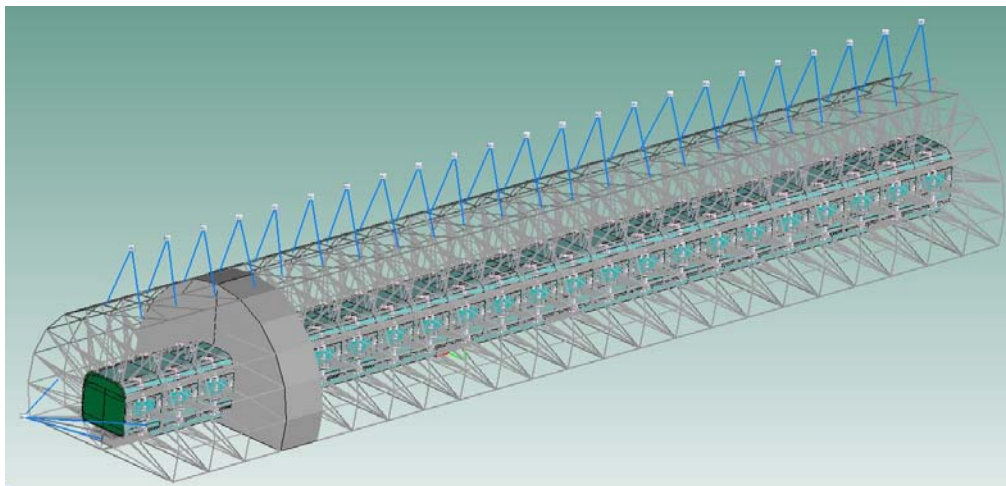


Figure 3: High frequency range vibroacoustic train model composed by different characteristic sections.

4. NOISE PREDICTION

As the analysis has been focused on the high frequency range the SEA model which is valid from 315Hz, is used. The precision in the flow detachment can be relaxed to the dimension of the characteristic train section discretization. For low frequency the pressure spectra for each element should be interpolated from the CFD mesh in the surface of the body to the structural mesh of the FE face of the FE structural subsystem by using a fluctuating surface pressure (FSP). Among the motivations for the use of the SEA is the computational time required is much smaller than the required in FE analysis, and FE is very sensitive to slight changes in input parameters.

In SEA due to the averaging over the points of observations the phase information gets lost. The averaging over the points of excitation the information about the shape of the individual eigenmodes is eliminated, so modes are no longer calculated. The last averaging is over the frequencies of excitation assuming more than 3 modes in the frequency band.

To introduce aeroacoustic load, the turbulent boundary layer excitation is implemented as the only aerodynamics power source, in order to study of attached and detached flow in the surface of the train.

In the figure 4, the PSD spectra of the attached and detached flow field for all sections and some sections in front of the train is plotted. It can be seen; when the flow is detached the acoustic load of turbulent boundary layer has increased nearly by 10 dB.

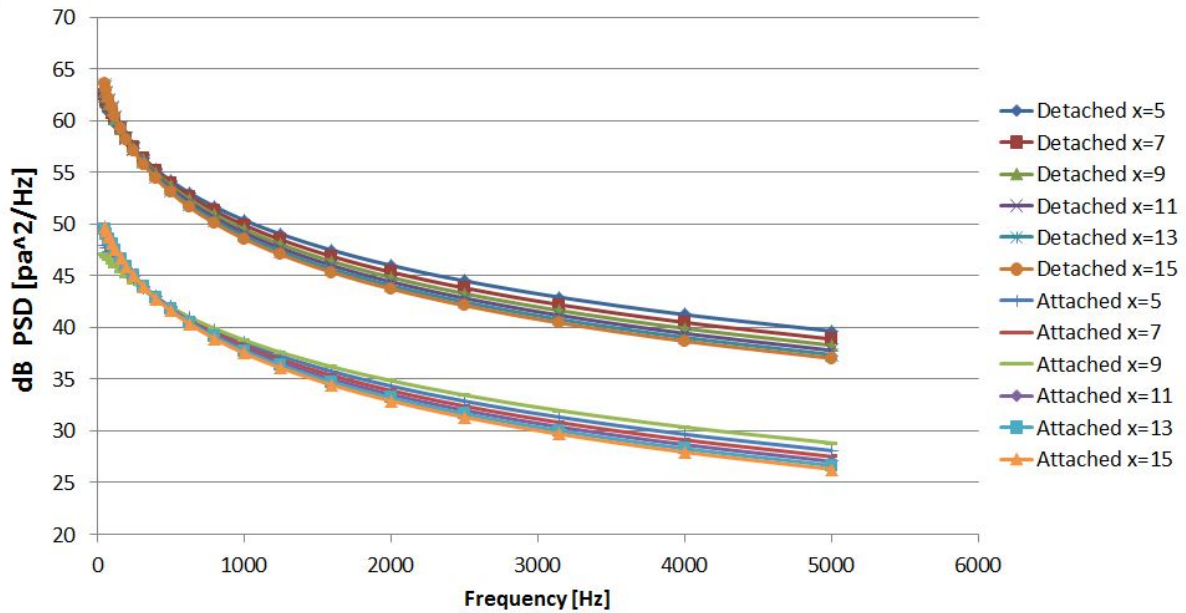


Figure 4: Acoustic load due to TBL source

By solving the model for different speeds, the sound pressure level inside the train obtained for both cases when the flow is attached and detached to the train surfaces. In the figure 5, each graph shows that by increasing the velocity, obviously the SPL for both types of flow (attached and detached) are increased. And by comparing these two graphs, it is cleared that separation flow increases SPL nearly 10 dB in overall for all the speeds.

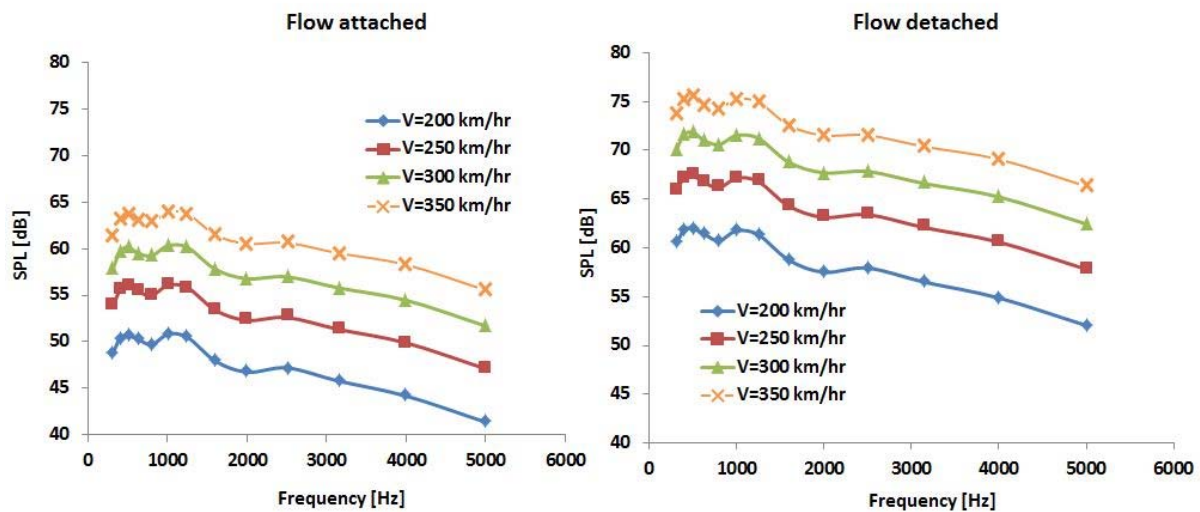


Figure 5: Sound pressure level of interior cavity when the flow is attached and detached for different speed

In the figure above, the attached flow and separated flow is considered for all the train sections to see the effects of different speed on SPL inside. Now, in the figure 6, the SPL inside the section at 11 m from the leading edge of the train travelling at 300 km/h is presented for several recirculation bubble sizes, supposing the flow reattaches at the end of the section at 5, 7, 9, 11, 13 or 15 meters to illustrate the effects of separation and reattachment. For instance, red line is when the flow is attached to all the train sections, the orange line is related to the flow when separated at the only first section and attached to the rest of the train sections. Respectively for the next sections till the highest SPL is related to detached flow for all sections.

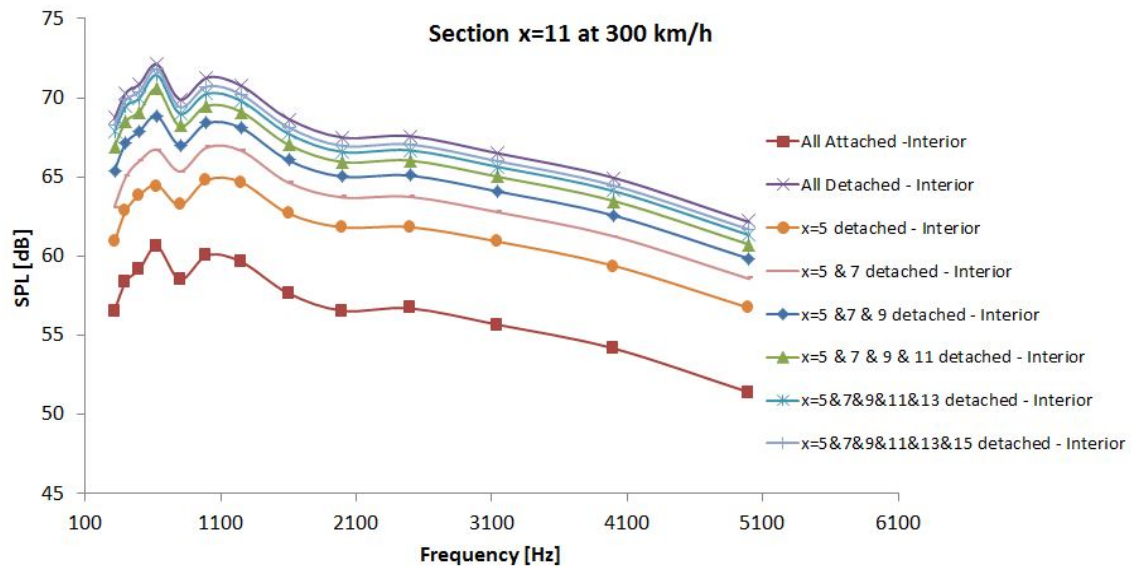


Figure 6: Sound pressure level of interior cavity at 11 meter from the nose of the train at speed of 300 km/h

In figure 7, the SPL inside the section at 11 m from the leading edge of the train travelling at 350 km/h is presented for several recirculation bubble sizes, supposing the flow reattaches at the end of the section at 5, 7, 9, 11, 13 or 15 meters.

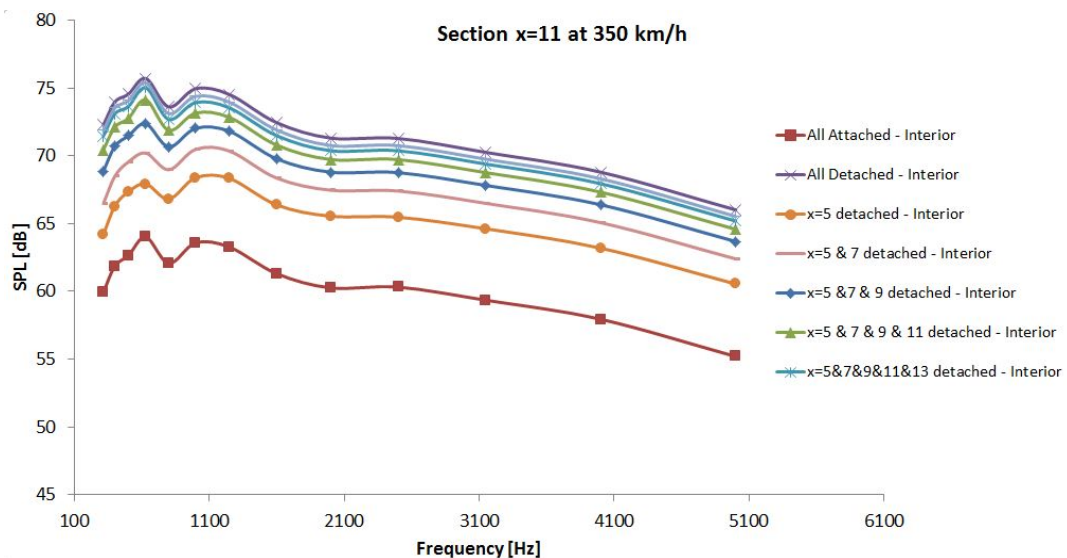


Figure 7: Sound pressure level of interior cavity at 11 meter from the nose of the train at speed of 350 km/h

In figure 8, the difference in the predicted overall sound pressure level A-weighted are presented for the different flow detachment sections hypothesis for the two different speeds, 300 and 350 km/h. in the graph, horizontal axis is the distance of separation, while zero means there is no separation and the flow is attached to all the train sections. As it can be seen, when the separation occurs in front of the mentioned section, the SPL increases dramatic, and as long as separation covers and passes the section, the SPL increases very slightly having the value very close to the case with all detached flow field on the whole train sections.

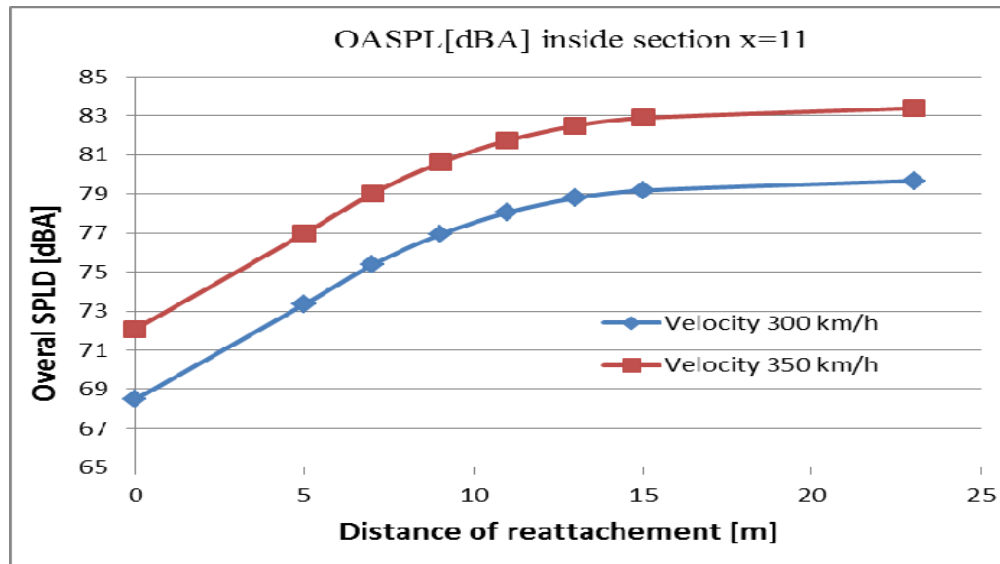


Figure 8: Deviation in OASPL [dBA] inside the train for attached and detached flow at 300 and 350 km/h.

As can be appreciated in the figure 8 the OASPL would exceed the maximum permitted in passengers cabin (65 dBA) already at 300 km/h, an improvement in the NCT should analyzed. The design of the NCT will be influenced by the probability of flow detachment, possibility of the recirculation bubbles of different sizes, due to a possible cross wind or to the pantograph configuration.

5. CONCLUSIONS

A study of the influence of the flow detachment has been presented. The importance to check the hypothesis of attachment has been highlighted with the parametric analysis of the detachment point is done. The flow detachment should be considered in NCT design in high speed trains.

In this work, a study of the influence of flow detachment has been presented. As a result the detachment can apply minimum 10 dB more to sound pressure level. The effect of separation is bigger than the effect of speed. For instance at the speed of 300 km/h with attachment flow field, SPL increases at least 10 dB when the flow becomes detached but SPL increases less than 10 dB if the speed increases from 300 to 350 km/s in the current attached flow field. Therefore, this makes clear the importance of knowing about separation regions and optimize the design.

As future work a scaled mock-up of a train is going to be tested in the wind tunnels with PIV, the measurements will be used to validate a DES simulation. The dynamic pressure spectra will be introduced in the vibroacoustic model as a fluctuating pressure surface and the results will be compared with the TBL given by default in VA One.

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